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**THE EFFECT OF VARYING BITING POSITION
ON RELATIVE JAW MUSCLE EMG ACTIVITY**

Dennis C. Dixon

A thesis submitted to the Faculty of the Graduate School
of the State University of New York at Buffalo
in partial fulfillment of the requirements
for the degree of Master of Sciences
in the Oral Sciences

September, 1988

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To my wife, Marguerite and family who both endured and supported my during the preparation of this thesis.

DEDICATION

This thesis is dedicated to my mother who dedicated her life to her children.

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ABSTRACT

Several numerical models that abstractly represent the masticatory system have been proposed. These models predict the distribution of forces among the muscles and the reaction force in the joint based on a given occlusal load. Little information is available regarding the accuracy of model predictions. The purpose of this study was to compare the pattern of model predicted jaw muscle forces (Smith, et al., J Dent Res 65:1046) with the pattern of EMG activity from those same muscles as a constant bite force was moved around the dental arch.

EMG recordings were made bilaterally from the anterior and posterior temporalis and masseter muscles of ten subjects while they bit with constant force on a transducer at seven positions around the dental arch. Both predicted model forces and EMG data were converted to standard scores allowing comparison of patterns at the various biting positions.

Our findings indicated low and relatively constant EMG activity in the posterior temporalis muscle as the bite position was moved anteriorly from the contralateral molar to the incisors. EMG activity rose sharply from the incisors to the ipsilateral canine and premolar area followed by decreasing activity in the molar area. Model predictions for the temporalis suggested a steadily increasing level of activity from the contralateral molar position around the arch to the ipsilateral molar position.

Anterior temporalis EMG activity patterns roughly followed the model's predictions except in the ipsilateral molar position where the model predicted higher activity than was suggest by the EMG activity pattern.

EMG activity patterns for the masseter showed symmetrically decreasing activity on the ipsilateral and contralateral sides from a high point of activity at the incisors. Model predictions for masseter suggested bilateral decreasing activity from the incisor area posteriorly, however, activity on the ipsilateral side was considerably higher than corresponding positions on the contralateral side. This model asymmetry was in contrast to the symmetry in corresponding biting positions observed in the EMG activity patterns.

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INTRODUCTION

Much of the information available regarding the mechanics of the masticatory apparatus has been gained by studying the question of the type of lever system the mandible represents and whether the condyle is load bearing during function (Hylander, 1975, Roydhouse, 1955, Gosen, 1974). The search for an answer to these questions has led to the development of several numerical models intended to abstractly represent the system (Pruim et al., 1980, Barbenel, 1972, 1974, Osborn and Baragar, 1985, Baron and Debussy, 1979, Smith et al., 1986). Closely related to the lever system idea is the role of the various masticatory muscles in producing bite force via their action on the mandible. Some of the models have attempted to integrate muscle function with the mechanical action of the mandible and joint working towards the goal of achieving a valid representation of the total physiologic system.

The numerical models utilize the principle that for an isometric bite the mandible is in static equilibrium, and therefore, the sum of the forces acting on it and the sum of the moment arms or torques around the condyles must total to zero. This principle allows formulation of several simultaneous equations. However, there are more unknown variables than equations, which requires using numerical minimization techniques to effect a solution. Two minimization hypotheses have been advanced. The first proposes that the system's goal is to protect the temporomandibular joint tissues and therefore minimizes joint force. The second hypothesis is that the system maximizes efficiency and therefore minimizes

total muscle force required to perform the demanded task.

Barbenel (1972) proposed a two dimensional model utilizing both the minimal total muscle force and minimal total joint force hypotheses. Dissatisfied with the results of the muscle force minimization approach, he later (1974) refined the joint minimization approach by adding EMG data to his equations. With this EMG data and multiple linear regression techniques, he calculated a constant that directly related EMG activity to muscle tension. Unfortunately, very little data were presented regarding muscle function under varying occlusal load conditions, and in both versions of his model, masseter activity was saturated before other muscles were activated. The simple technique of palpating one's own muscles during light occlusal loads verifies that other muscles become active early in the generation of bite force.

Osborn and Baragar (1985) expanded Barbenel's (1974) model to a quasi-three dimensional design. By partitioning the larger muscles into two or more smaller elements, a total of 13 independently functioning muscle elements were designated on each side. Also included were the digastric muscles. This approach also produced many variables and again, minimization techniques were required to reach a solution. Solutions were obtained for both joint force and total muscle force minimization.

In the joint reaction force minimization approach, combinations of lateral pterygoid and posterior temporalis muscle forces could maintain joint force at zero. However, these muscles became saturated at biting forces over 13 kg after which joint forces rose rapidly. Since EMG data did not support this outcome, they

concentrated on the muscle force minimization approach. Common to both the Barbenel (1974) and the Osborn and Baragar (1985) models is the characteristic that muscles with the longest moment arms are recruited first and saturated before the next muscle with the next smaller moment arm is recruited. However, by dividing muscles into elements, Osborn and Baragar's (1985) model allowed alternating activation of elements between overlapping muscles according to the principle of longest moment arm instead of being limited to having entire muscles activated sequentially.

Although Osborn and Baragar's (1985) model may be capable of solving three dimensional asymmetric loading problems, all results presented were from symmetric occlusal loads which produced symmetrical muscle and joint reaction force solutions. As such, the model is essentially two dimensional.

A more versatile model, at least in its capacity to accept asymmetrical input loads from a variety of directions, has been proposed by Smith et al., (1986). This model limited its consideration of muscles to the temporalis and lateral pterygoid and treated the masseter/medial pterygoid sling as a single functional unit. This model is truly three-dimensional in that it is capable of predicting resultant condylar forces in three dimensions and can calculate asymmetric muscle forces for unilateral occlusal loads.

Other investigations have directly addressed patterns of muscle activity through the use of electromyography in an attempt to describe actual function without consideration of a model or control system that determines how the occlusal load is divided among the muscles. Linearity of EMG activity with muscle force is the key to

this approach as it allows inference of muscle contraction activity from EMG data. This relationship has been the subject of many investigations (Lippold, 1952, Barbenel, 1974, Pruim et al., 1978, Kawazoe et al., 1979, Hagberg et al., 1985, Kull, 1988). The common conclusion was that a linear relationship is present at least at submaximal force levels.

Most direct muscle function studies are based almost exclusively on EMG monitoring of muscle activity under a variety of biting and chewing conditions. MacDonald and Hannam (1984a) recorded EMG activity while subjects bit on custom formed, acrylic, occlusal stops placed in sequence at the molar, canine and incisor positions. They did not control for bite force which likely varied between biting positions making ipsilateral to contralateral comparisons difficult. Extensive EMG activity studies have been conducted regarding kinesiology of chewing (Ahlgren, 1967, Carlsoo, 1956, Moller, 1966), but they did not adequately address static isometric biting conditions necessary to relate their data to model predictions. Other than Barbenel's 1974 and Pruim's et al. 1980 studies, very little effort has been directed at evaluating and refining the models in terms of information from EMG activity studies of muscle function.

Therefore, the purpose of this investigation was to design an EMG activity study with controlled bite forces directed specifically at a limited area of model predictions with the intention of investigating the model's validity compared to actual physiologic function and to begin accumulation of a body of data that can be applied to refining the models. The hypothesis, formally stated, was: There is no

significant difference between the pattern of muscle forces predicted by the Smith et al. (1986) model and the pattern of EMG data as the point of application of a constant bite force is moved around the dental arch.

LITERATURE REVIEW

Introduction: The study of the physiology of bite force, muscle contraction force, joint reaction force and the lever system the mandible represents has held the interest of investigators for many years (Hylander, 1975, Roydhouse, 1955, Gosen, 1974). A long history of effort in this area has led to the development of several numerical models intended to abstractly represent the system. (Pruim et al., 1980, Barbenel, 1972, 1974, Osborn and Baragar, 1985, Baron and Debussy, 1979, Smith et al., 1986).

Integral to this system is the role of the various masticatory muscles in producing bite force via their action on the mandible. Knowledge regarding muscle force produced during bruxing and other parafunctional activity would be clinically useful in relating symptoms to specific muscle activity patterns. Since muscle or joint reaction forces cannot be practically measured in humans, a model that accurately predicted these parameters would be an invaluable aid in determining etiology and possibly suggesting treatment modalities for some temporomandibular disorders. Several models have been proposed, but very little experimental work has been accomplished to establish their validity. Electromyographic (EMG) studies appear to be one of the best methods of testing model predictions of muscle forces. EMG evidence supporting the models' predictions of muscle force would also support the validity of the models' predictions of joint reaction

forces.

ELECTROMYOGRAPHY and MUSCLE FORCE: Direct measurement of force production by individual human muscles is impractical due to their inaccessibility. Currently, the best method of indirectly observing muscle contraction activity is through electromyography. Although there appears to be a time delay between onset of peak EMG activity and peak contraction activity of between 40 and 80 ms (Ahlgren and Owall, 1970, Hannam et al., 1975), EMG activity is an excellent, relatively uncomplicated indicator of the onset and cessation of muscle contraction activity. Inference of muscle contraction force from EMG activity is more complicated.

Several investigators have demonstrated a linear relationship between EMG activity magnitude and muscle contraction force.

Lippold (1952) found a close linear approximation of EMG activity to submaximal isometric muscle tension in gastrocnemius-soleus muscle group with a correlation coefficient of between .93 and .99. Inman et al. (1952) found the same relationship and noted that linearity failed when muscles were stretched indicating the need to maintain strict isometric conditions.

In the masticatory system, the relationship of individual muscle force to total bite force may be more complicated due to the intricate interplay of multiple muscles producing the bite force and their changing role with varying biting conditions. These factors might be expected to intervene in the jaw muscle force to EMG

activity relationship. However, a general linear relationship has been noted in the masticatory muscles with some disagreement regarding conformity near the maximum effort range. Specifically, Pruim et al. (1978) noted accelerating change in the EMG activity to force slope in the masseter and posterior temporalis muscles which he attributed to concurrent antagonistic activity in the opener muscles. Hagburg et al. (1985) found a decreased slope for the masseter muscles at effort levels of 0 to 40% of maximum and a steeper slope at effort levels of from 60 to 100% of maximum effort. In the anterior temporalis muscle, the slopes in these same areas did not differ. She attributed the departure from linearity in the masseter to difference in recruitment patterns of the differing muscle fiber types between the two muscles. From a visual inspection of the masseter scattergram data however, it would appear that a near linear relationship was present over the first 90% of the data. The steeper slope in the 60-100% bite force effort range may have arisen from a sharp increase in EMG activity in the last 10% of the data. Barbenel (1974) confirmed a linear EMG activity to force relationship for both the masseter and temporalis muscles. Using a numerical model he was able to calculate a proportionality constant to directly relate EMG activity to force. However, the constant varied from muscle to muscle and with different biting conditions making its broad application difficult. Kawazoe et al. (1979) also found EMG activity linearity over the range of increasing force during a rapid clench. Rapid clenches may

not be ideal assessment conditions due to the lag between peak EMG activity and peak muscle force activity discussed above. Finally, Kull (1988) found linearity over the entire voluntary effort range for both the temporalis and masseter for an ipsilateral molar bite on a custom fitted acrylic bite plate. Maximum effort nonlinearity may not have been observed due to proprioceptive inhibition from the unilateral bite and small amount of tooth area covered by the bite plate.

Pruim et al. (1978) has also suggested that nonlinearity in specific areas of the force range may be due to an altered relationship between individual muscle EMG activity and total bite force while the the linear relationship of individual muscle force and its EMG activity is preserved. The consensus from most studies indicates the there is a generalized linear relationship of EMG activity to bite force at least through most of the submaximal voluntary force range although the proportionality constant relating force to EMG activity probably varies between muscles and biting conditions.

EMG ACTIVITY RECORDING: There are four commonly used electrode techniques in EMG activity studies. (1) Bipolar surface electrodes adhered to the skin by tape with electrical contact maintained through conductive electrode gel. (2) Fine-wire electrodes inserted into the belly of the muscle with a hypodermic needle. (3) Concentric needle electrodes that record from the small

bared central tip and the complete sleeve when inserted into the muscle. (4) Bipolar needle electrodes that record from two small tips near the point of the needle when inserted into the muscle.

Basmajian (1974) has criticized surface electrodes as they can be used only for muscles located near the dermal surface and their pick-up area is too widespread. He suggests that their best use may be in monitoring the activity in a fairly large group of muscles where palpation is awkward, e.g. during rapid movements. He prefers fine-wire electrodes due to their relatively easy and painless application, ability to detect activity from single motor units while maintaining the capacity to monitor total muscle EMG activity. He contends that the concentric needle electrode is extremely localizing if the sleeve is insulated and if it is not insulated, the electrode records from its entire imbedded length and may pick-up activity from nearby muscles. Wood (1987), on the other hand, maintains that fine-wire electrodes could move in the muscle during contractions and may become entirely displaced during recording from small muscles like the superior head of the lateral pterygoid. He agrees with Basmajian that concentric electrodes may pick-up activity from adjacent muscles via the uninsulated sleeve. Also, he concedes that surface electrodes may pick-up nearby muscle activity, but in most instances, this is cancelled by the differential amplifier. On the other hand, several investigators have found surface electrodes to be effective for recording from the superficial masseter and anterior and posterior

temporalis muscles (Belser and Hannam, 1986, MacDougall, 1953, Ahlgren, 1967). Belser and Hannam (1986) placed fine wire electrodes between bipolar surface electrodes that were 20 mm apart over the body of the masseter muscle. They found no significant difference between recordings from the surface and fine-wire electrodes for chewing and maximum clenching. It appears that surface electrodes are adequate for recording global EMG activity from accessible muscles.

MUSCLE FUNCTION: Investigations into the roles of the individual muscles during clenching in various eccentric jaw positions have used EMG activity almost exclusively. A group of studies, to be discussed below, investigating muscle activity in various clenching or bruxing positions had as one of their goals the correlation of specific muscle activity during bruxing acts and patterns of muscle tenderness seen in temporomandibular disorder patients. Correlation of wear facet patterns and specific mandibular positions during bruxing with patterns of muscle tenderness might be clinically useful.

Maximum EMG activity of the masseter, temporalis, and in most instances, medial pterygoid occurred in an intercuspal vertically directed maximum clench (MacDonald and Hannam, 1984b). Using these maximal effort EMG values as a standard, a percentage of maximum EMG activity could be determined for bites other than maximum effort allowing rough comparison of activities between

different biting situations.

Of particular interest were clenching positions where a difference in activity levels could be observed between the anterior and posterior temporalis, the superficial and deep masseter, and the medial pterygoid and masseter. In an intercuspal clench with posteriorly directed effort, activity in the anterior temporalis decreased compared to maximal vertical effort while the posterior temporalis contracted maximally. The superficial masseter and medial pterygoid ceased activity while the deep masseter was maximally active (Wood, 1986, Belser and Hannam, 1986). This pattern of activity implied that the direction of the deep masseter fibers assisted retrusive movements as did the posterior temporalis while the superficial masseter and medial pterygoid fiber direction was antagonistic to retrusive movements. Also shown here was independent activity of anatomically different parts of the same muscle.

In the opposite situation where force was directed anteriorly from the intercuspal position, posterior temporalis activity ceased while the deep masseter's activity decreased. Medial pterygoid and superficial masseter were maximally active (Wood 1986, Belser and Hannam, 1986). In laterally directed effort from the intercuspal position, contralateral temporal muscle activity ceased as the ipsilateral muscle was active. The contralateral medial pterygoid activity was high while the ipsilateral medial pterygoid activity was low. In contrast, the contralateral masseter activity was low

while the ipsilateral activity was high (MacDonald and Hannam, 1984b). Under biting conditions where the canines are edge to edge, ipsilateral masseter muscles were more active than contralateral masseter while contralateral medial pterygoid was more active than ipsilateral medial pterygoid. Apparent again was the independent action of sections of the same muscle and of closely related muscles.

Bite force was not controlled in any of these studies. Therefore some of the EMG activity changes found in different biting positions could have been the result of undetected changes in bite force as well as changes in position and direction of effort. Wood (1987) proposed that clenching on anterior teeth caused the temporalis muscles to cease activity. This may not be the case however in subjects with significant anterior wear facets allowing multiple simultaneous contacts. Moller (1966) has suggested that muscle activity magnitude and distribution is dependent of the number of occlusal contacts, and MacDonald and Hannam (1984a) found clearly increased temporalis activity when subjects bit on an acrylic block that covered from canine to canine compared to a small block that covered only the central incisors.

MUSCLE MASS AND LINE OF ACTION: Accurate estimation of force produced by individual muscles of mastication is critical to understanding the dynamics of jaw function. One method of estimation involves determining a proportionality constant between

muscle cross-sectional area and force capability (Gysi, 1921). Mainland and Hiltz (1934) assessed the force direction and cross-sectional area of the superficial and deep masseter, medial pterygoid and anterior and posterior temporalis muscles. They concluded that skeletal muscle is capable of exerting an average maximum of 10 kg per square cm of muscle mass. Using this proportionality constant and the cross-sectional area, they calculated the upper force limit capacity for each muscle. However, they conceded that the proportionality constant varied widely with muscle fiber type and from individual to individual. Cross-sectional area also varies widely among individuals, sexes and age groups. However, fairly accurate determination of cross-sectional area may be possible in live subjects using computed tomography. Weijs and Hillen (1984) compared tomographic assessments of cross-sectional area with dissected cross-sectional assessment techniques in cadavers and found a high correlation between the two techniques. He concluded that computed tomography can provide a relatively easy and fairly accurate way to determine physiologic cross-section of jaw muscles in living subjects.

A modification of the cross-sectional area method of determining individual muscle force output involves the use of linear relationship of EMG activity to muscle force. Pruim et al. (1980) formed a ratio of the maximum force values obtained from cross-sectional area studies to the maximum EMG activity recorded from a muscle. This provided a proportionality constant that allowed force

calculation of individual muscle force for specific EMG values. This method depends heavily on the estimates of maximum force from cross-sectional area and unless some method is used to assess individual subject's muscles, losses of accuracy due to individual differences in muscle mass, sex, age, and dental status may be significant.

Barbenel (1974), using multiple linear regression techniques, attempted to calculate EMG to force proportionality constants by analyzing the equations relating muscle lever arms, the bite force lever arm and recorded EMG activity. However, no data were presented to support the validity of this method of calculating proportionality constants.

The direction of individual muscle force and the point on the mandible where the force is applied are critical to calculation of total system equilibrium. Muscle force direction determines the vertical component of the force and the length of the moment arm generated by the muscle (Throckmorton, 1985). Several investigators have attempted to represent muscle force direction by lines drawn connecting the centers of origins and insertions (Pruim et al, 1980, Carlsoo, 1956a). Baron and Debussy (1979) presented a detailed three dimensional analysis of 12 major muscle fascicles on five human skulls. They described the mean coordinates and standard deviation of the origin and insertion of each of the fascicles related to a set of three orthogonal axes. They attributed these means to be representative of the "average" man. However,

they found that the variances of some of the coordinates were substantial. The larger variances tended to occur in fascicles with extended areas of attachment such as in the masseter, medial pterygoid and temporalis or in areas where skeletal geometry patterns differed. A logical conclusion from these studies is that there is substantial error involved in estimating origins and insertions of muscles even when the detailed anatomy of dry human skulls is available. Determination of these coordinates in live subjects is likely to be even more inaccurate.

In a study on the effect of muscle insertion and origin point measurement errors, Throckmorton (1985) found that the major effect of errors in the assessment of muscle force direction are their influence on the length of moment arms. The analysis showed that errors in muscle force direction had greater effect on the calculation of joint reaction forces than did errors in muscle force magnitude.

Weijs (1980) has suggested that during biting, the mandible is supported in several directions by the muscles and in at least three points (bite point and two joints). Many combinations of muscle forces can therefore lead to a balanced static situation. Hylander (1979) found variations in strain directions of the mandible in the Macaca monkey while repeating a biting task. He attributed the changing strain patterns to variation in the pattern of muscle loading on the mandible. This changing pattern of muscle activity, even though biting conditions do not change, could result in a variety

of muscle and joint load solutions for the same static biting task.

In summary, there appear to be several factors that have considerable effect on the proportionality constant relating EMG amplitude to bite force. These include the direction of muscle fibers which affects length of the moment arm, the cross sectional area of the muscle or its maximum force production capacity, and possible changes in the effective origin and insertion points due to independent activity in different fascicles within the muscle. Currently, these variables cannot be accurately defined for individual subjects and this undoubtedly accounts for some of the variability observed when bite and individual muscle force is being inferred through the use of EMG activity.

BIOMECHANICAL MODELS: Several mathematical models designed to simulate the masticatory apparatus have been proposed (Pruim et al., 1980, Barbenel, 1974, Osborn and Baragar, 1985, Smith et al., 1986). The primary purpose of most models was to investigate the presence and magnitude of temporomandibular joint loading forces. However, calculating joint forces requires the concurrent calculation of muscle forces acting on the mandible and therefore, the models are a valuable source of information regarding the interplay of the individual muscles in the production of bite force.

The models treat the mandible as a static rigid body that is in equilibrium with all the forces acting on it during a static isometric bite. Therefore, the sum of the muscle, bite, and condylar forces

acting on the mandible and the rotational moments or torques must total to zero. These static equilibrium principles form the basis for the analysis of forces performed by the models.

Barbenel's (1974) model allowed muscle force direction input in three dimensions, but considered occlusal loads and condylar reaction forces in only two dimensions. Therefore, equilibrium solutions were only obtainable for situations in which muscle activity and occlusal loading were equal on each side of the mandible and as a result, this is essentially a two dimensional model. A three dimensional coordinate system was centered about the condylar axis with the yaxis parallel to the Frankfort plane. Three equations were derived from the equilibrium situation where the sum of the force components in the y direction is zero, the sum of the force components in the z direction is zero and the sum of the moments about the condylar axis is zero. The unknown variables in the equations are the forces exerted by the temporalis, medial and lateral pterygoid, and masseter muscles, and the joint reaction forces. The occlusal load is given. These equations can be solved with linear programing techniques for the minimum joint load compatible with equilibrium. To solve the equations for muscle forces, additional equations are required. Barbenel then used multiple linear regression to find proportionality constants for each of the muscles. Individual muscle force could then be derived from EMG activity measurements. Since no data were presented regarding the balance of forces among the muscles under various occlusal

loads and angles, no assessment of validity of the models muscle force predictions is possible. However, the model's limitation of considering only biting situations in which the occlusal load and muscle activity are symmetrical prevents it from being applicable to most naturally occurring biting situations since they are asymmetric.

Pruim's et al. (1980) model was purely two dimensional. His equilibrium equations were similar to Barbenel's (1974), but instead of using multiple regression techniques to calculate proportionality constants, he used muscle cross-sectional area to determine maximum force capacity for individual muscles. The maximum EMG activity recorded from a muscle could then be related to the maximum force capacity for the muscle to give the proportionality constant. Subjects performed maximum effort voluntary clenches on a transducer that distributed forces evenly to both sides of the mandible. Thus, magnitude and point of application of bite force was known. Simultaneous recording of EMG activity allowed calculation of individual muscle force and joint reaction force. The data indicate that the greatest bite force and muscle activity occurred in the first molar region, followed by second molar and first premolar regions. This model, as well as Barbenel's (1974), did not deal with asymmetric occlusal and muscle loads. Also, the model assumed that muscle cross-sectional area and therefore maximum muscle force capacity does not vary across subjects. The primary purpose of both Barbenel's (1974) and Pruim's (1980) models was to assess

the magnitude of condylar loading. The model succeeds in this only to the extent that the input parameters were accurate. Here again, the inaccuracies of assigning muscle force direction and muscle cross-sectional area become factors.

Osborn and Baragar (1985) sought to improve on Barbenel's early model (1972), by suggesting that Barbenel's technique of minimizing the sum of the total muscle forces erred by selecting and saturating the entire muscle with the longest moment before the muscle with the next longest moment arm was activated. This resulted in a "ripple effect" or sequential activation and saturation of entire muscles before other muscles are activated. Sequential activation can easily be shown not to occur in nature by simply palpating one's own masticatory muscles while slowly increasing bite force.

Osborn and Baragar (1985) also contended that Barbenel's (1974) treatment of large broad based muscles such as temporalis and masseter as a single unit represented by a point origin and insertion resulted in no overlap of different muscles vectors or lines of force while *in vivo* muscles, such as masseter and medial pterygoid, have considerable overlap of muscle fibers. Osborn and Baragar's (1985) approach was therefore, to divide broad muscles into two or more elements assuming that each element could contract independently. Although muscle elements were still activated sequentially in order of decreasing moment arm length, elements of muscles that overlapped were activated alternately between muscles instead of muscles in their entirety being sequentially activated as in

Barbenel's (1974) approach. The ripple effect remained, but it was dispersed among the elements of different muscles.

Osborn and Baragar's (1985) model was three dimensional with x , y , and z input coordinates for each muscle element and both condyles. Thirteen bilateral muscle elements, resulting in 28 force variables including the condyles, were included in the equilibrium solution. Linear programming was used, as in Barbenel's (1972) first model, to solve the static equilibrium conditions for minimum joint force and for minimum condyle reaction force.

Although Osborn and Baragar's (1985) model was apparently capable of three dimensional asymmetric calculations, it was used in this theoretical study to produce only two dimensional solutions in which occlusal load input and resultant muscle and condyle reaction forces were symmetrical. In the joint reaction minimization solution, the posterior temporalis and upper element of the inferior head of the lateral pterygoid could neutralize joint reaction forces for occlusal loads of less than 13 kg by exerting appropriate horizontal forces. At occlusal loads of more than 13 kg, these muscles became saturated and joint force rose rapidly. EMG activity studies of the lateral pterygoid and posterior temporalis muscles (Carlsoo, 1956b, Lehr and Owens, 1980, Wood et al., 1986, Wood, 1987, McNamara, 1973) do not support this pattern of muscle activity.

Therefore, the joint reaction minimization approach was discontinued in favor of total muscle force minimization. As in

Pruim's et al. (1980) model, maximum muscle forces were calculated from cross-sectional areas. Maximum bite force could be calculated using the maximum capacity force of individual muscles. Joint reaction forces were less than those calculated by Pruim et al. (1980) due largely to the stress relieving effects of inferior head of the lateral pterygoid as it pulled the condyle down and forward helping to unload the condyle. Pruim et al, (1980) represented the lateral pterygoid as a single horizontally directed force which actually increased joint reaction force.

The underlying philosophy of the Osborn and Baragar (1985) model is that broad muscles are used most efficiently by sequentially activating elements from their anterior border posteriorly (Ripple Effect). This idea is corroborated by the major power closing muscles having similar length moment arms allowing the ripple effect to alternate between muscles, i.e. masseter, medial pterygoid and anterior temporalis. If one of these muscles had a moment arm significantly shorter than the others, it would be of little use as a power muscle compared to the others. Complementary to the power closing muscles with long moment arms are the control muscles with shorter moment arms but lines of action that act to control antero-posterior movement of the condyle.

No experimental data were presented in the study to validate model predictions. An attempt was made to correlate findings with data published by Pruim et al. (1980). Notably missing from the paper was information on how the model would handle asymmetric

occlusal loads producing asymmetric muscle forces. This model implies that a very precise system for activating muscle elements is in place and that the activation sequence is optimized to minimize total muscle force required for the current biting task. No EMG evidence exists indicating that elements within the same muscle are activated sequentially from anterior to posterior as bite force increases. Hylander's (1979) evidence from Galago and Macaca monkeys indicates that differences in mandibular strain patterns occurred when subjects repeatedly bite on a transducer at submaximal force levels in the same biting position and with the same force magnitude. He suggested that differing strain patterns indicated differing patterns of muscle activity even though bite position or magnitude did not change. This indicates that, at least in monkeys, force distribution among the muscles does not follow a precise reproducible pattern. If this phenomena is present in humans as well, it may indicate that total muscle force minimization is not the schema that guides force allocation between muscles.

Smith et al. (1986) proposed a three dimensional numerical model incorporating the right and left temporalis, lateral pterygoid, and masseter/medial pterygoid slings, the temporomandibular joint, and bite force input that could be applied anywhere along the dental arch from any three dimensional angle above the occlusal plane. Thus, unlike the previously discussed models, Smith's et al. (1986) model can calculate equilibrium solutions for asymmetric occlusal, muscle

and joint loads.

The underlying schema for Smith's et al. (1986) model, in contrast to Osborn's and Baragar's (1985), was minimization of joint reaction force. As in Pruij's et al, (1980) and Barbenel's (1974) models, muscle force directions were represented by a line drawn from the center of the origin to the center of the insertion. Individual specific geometries for muscle origins and insertions, location of condyles and the occlusal plane, and length of the dental arch could be entered in the program to produce solutions customized for individuals.

Unlike the previous models, an iterative process solving for the root mean square of the joint reaction force was utilized instead of linear programming. First, an arbitrary muscle force solution that satisfied the equilibrium equations for given a bite force of specified magnitude, point of application and direction was calculated. One muscle force was then varied, and a new solution calculated. The previous solution was compared with the current solution to determine if a lower root mean square condylar force was achieved. The process was repeated with the components of muscle forces in each direction and the moments about each axis until the combination of muscle forces that produced the least condylar force was found.

The primary purpose of Smith's et al (1986) model, as in the other models, was to assess joint reaction forces. In this respect, it surpasses the other models in its ability to predict joint reaction

forces for a wide variety of asymmetric occlusal loads as the other models were limited to assessing symmetrically applied loads. The model does not attempt to ascribe maximum capacity contraction forces to the muscles by relating muscle cross-sectional area to force. As a result, there is no limit on individual muscle force capacity. It is conceivable that the model could calculate implausible solutions by assigning a force to one or more muscles that exceeds its force production capacity.

Since joint reaction forces, the minimization of which guide the direction of the model's solutions, cannot be directly investigated in humans, another method of assessing the models validity must be found. To achieve a solution for minimum joint reaction, force assignment must be made to each muscle. As the point of occlusal load is changed on the dental arch, the model predicts a concurrent pattern of changes in muscle force which should be reflected in a similar pattern of EMG activity changes. An EMG activity pattern that follows predicted model force changes would tend to validate the model and its operational theme, i.e. that the masticatory system functions to produce bite force in a way that minimizes joint reaction forces.

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METHODS AND MATERIALS

Subjects: After giving informed consent, ten adults, six males and four females, ranging in age from 26 to 47 years with a mean age of 39.1 years volunteered as subjects. Each subject had a full dentition, normal range of mandibular movement and reported no significant pain or dysfunction of the temporomandibular joint or masticatory muscles. Class I, II, and III occlusions were represented in the sample.

Bite Forces: The stainless steel bite force transducer consisted of two arms in a fork like arrangement with biting tabs extending from the arm ends (See figure 1).

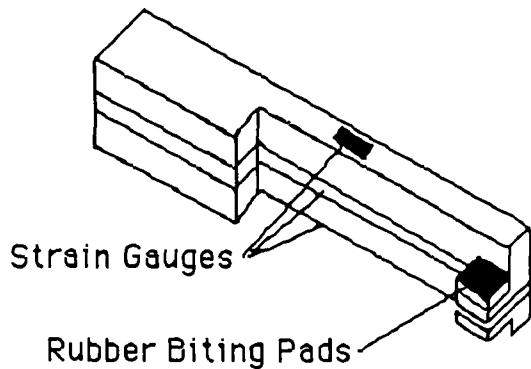


Fig. 1. Diagram of force transducer showing location of rubber pads on the biting tabs and strain gauges.

Four strain gauges positioned on the arms formed a Wheatstone Bridge. The bridge output was amplified and displayed on an oscilloscope where it provided feedback to the subject regarding performance of the biting task. The transducer was weight calibrated and found to be linear ($r = .9999$) over a range of zero to 300 N and the reliability of the transducer was verified before each data collection session.

Electromyography: Bipolar surface electrodes were attached to an acrylic template maintaining a fixed 20 mm interelectrode distance. The electrode pairs were placed over the fleshy portions of the right and left anterior temporalis, posterior temporalis and masseter muscles as shown in figure 2 (Pruim et al., 1980). A grounding electrode was placed on the ear lobe. Electrode impedance was maintained below 10 kohms. The six amplified EMG signals and the bite force signal were recorded on an eight channel magnetic tape recorder and replayed through a polygraph. EMG polygraph tracings were hand measured using a Boley gauge.

Experimental Procedure: The biting task consisted of producing constant bite force on the force transducer at each of seven randomly presented bite positions as shown in figure 3.

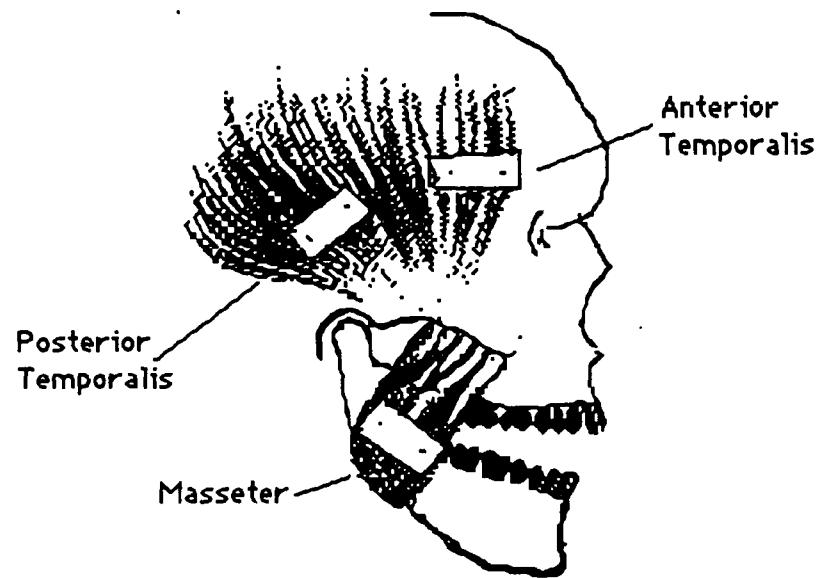


Fig. 2. Diagram of bipolar surface electrode placement over the anterior and posterior temporalis and masseter muscles bilaterally.

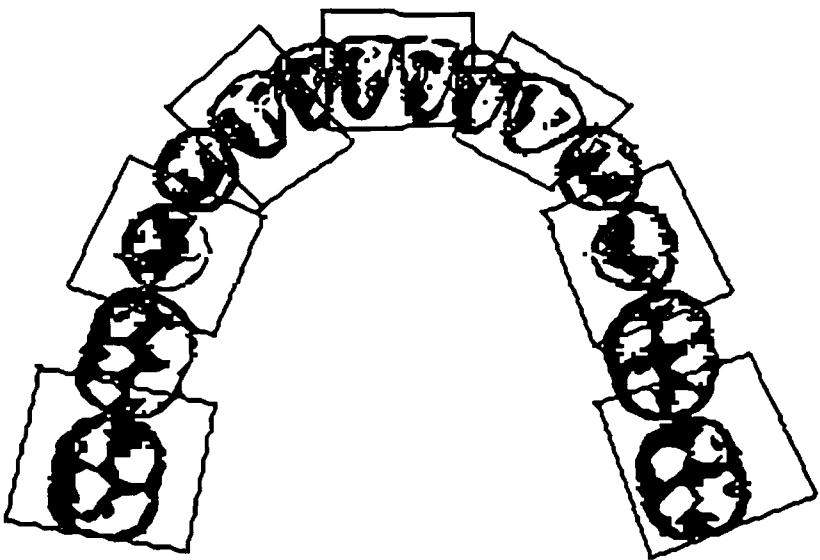


Fig. 3. Diagram of mandibular arch with rectangles representing the positions of the force transducer over the seven biting positions.

Subjects were requested to perform an incisor bite on the transducer of the greatest sub-discomfort force possible. This force was then matched at each of the biting positions. Note that the biting task simulated as closely as possible the parameters from which the model prediction was made, i.e. a force of constant magnitude was applied at specified positions along the dental arch. Changes in vertical dimension were minimized by varying the thickness of the rubber pads covering the biting tabs for anterior and posterior biting positions resulting in approximately 7 mm separation of the posterior teeth. Maintaining a centered incisor edge to edge relationship at each bite position minimized mandibular position changes in the horizontal plane and also contributed to

maintenance of isometric muscle contraction conditions. Three bites of three seconds duration were performed at each of the seven biting positions. No attempt was made to standardize the inter-subject bite force which ranged from 100 to 160 Newtons.

RESULTS

Typical EMG activity tracings are given in figure 4. Changes in EMG amplitude are clearly visible as bite position changes resulting in a varying mix of jaw muscle activity even though a constant bite force was maintained.

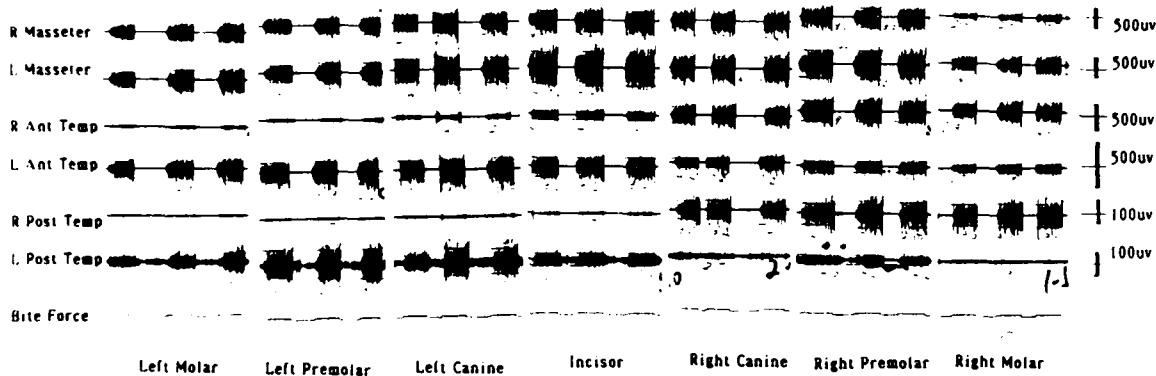


Fig. 4. One subject's polygraph data. Note three EMG bursts at each biting position. Also, note equal magnitude of bite force at each bite position (bottom row).

Data Conversion: Because the purpose of this investigation was to compare patterns of EMG amplitudes with predicted force amplitude patterns, both EMG and force magnitudes were converted to standard scores. This conversion preserves the trends of rising and falling patterns of muscle activity among bite positions while confining the variation among subjects within a common range. The following technique was used to convert the data to standardized form from which patterns of muscle activity were inferred.

EMG values from the set of three bites at each position were averaged to obtain a mean EMG value for each bite position. Within each muscle, the mean EMG activities of the seven biting positions, were converted to standard scores. Standard scores were then combined across subjects to obtain a grand mean and standard deviation at each bite position. Standardized EMG data from one subject's masseter muscle for the seven biting positions is shown in figure 5. The combined means and standard deviations from all subjects appear graphically in figures 6 through 9 and 12 and 13.

The same conversion technique was used to obtain standard scores for the model's prediction of muscle forces. Converting both EMG measured microvolt units and muscle force measured in Newtons units into dimensionless standard score units allowed direct comparison of the pattern of muscle forces predicted by the model with the pattern of EMG activity for the same muscles (See figures 6 - 9 and 12 - 13).

Statistical Analysis: Quantitative analysis of the data was accomplished using a one-way repeated measures analysis of variance. Overall, significant differences in EMG activity among the seven biting positions were found in each of the muscles at the $p < .001$ level. In order to localize specific sources of variation and also to identify positions where muscle activity did not vary to any great extent, two pairwise post hoc tests were performed on all combinations of bite position pairs within each muscle. A liberal test, Fisher's Least Significant Difference Test (FLSDT), at the alpha

= 0.1 level (Miller, 1966) was used to increase the likelihood of finding significant differences between pairs of biting positions. This test and the large alpha were chosen to increase the validity of proposing that the EMG activity of two bite positions being compared

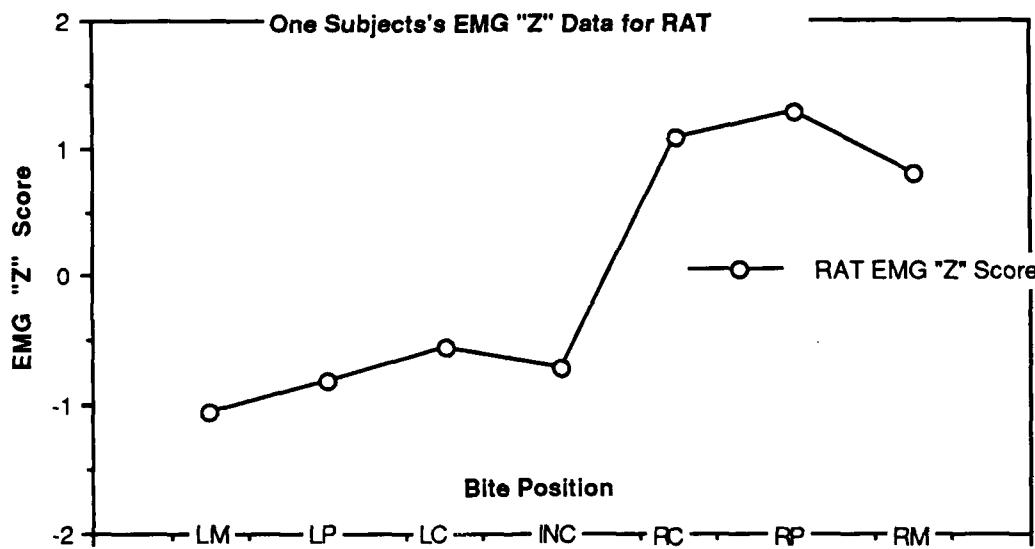


Fig. 5. One subject's standardized EMG activity data for the right anterior temporalis. LM = left molar, LP = left premolar, LC = left canine, INC = incisors, RC = right canine, RP = right premolar, RM = right molar.

were not significantly different when found so by the test. When this test found no significant differences between pairs, it was inferred that no distinctly increasing or decreasing pattern of activity was present. The conservative test, Sheffe's pairwise test

(alpha = .05) was also performed on all combinations of bite position pairs. When significant differences were found between positions with this test, it was inferred that a distinct difference in EMG activity was present. The following is a description of patterns of muscle activity as identified by the above criteria.

Posterior Temporalis Muscles: Inspection of the posterior temporalis graphical data in figures 6 and 7 suggests a relatively unchanging low EMG activity on the contralateral biting side from the molar to the incisor biting positions, a rising trend to the ipsilateral canine, and a downward trend from the canine to the ipsilateral molar.

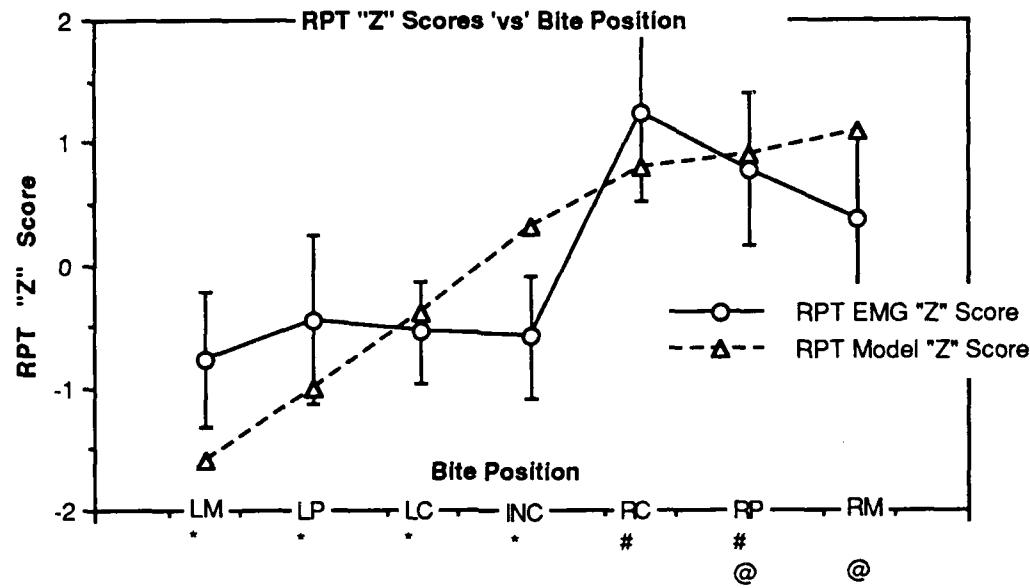


Fig. 6. Right posterior temporalis standardized EMG score means shown as circles connected with solid lines. Vertical lines are one standard deviation error bars. Model predictions for the right temporalis muscle are shown as triangles connected by dotted lines. Mean EMG values at biting positions labeled with the same symbols, e.g. "*" are not significantly different.

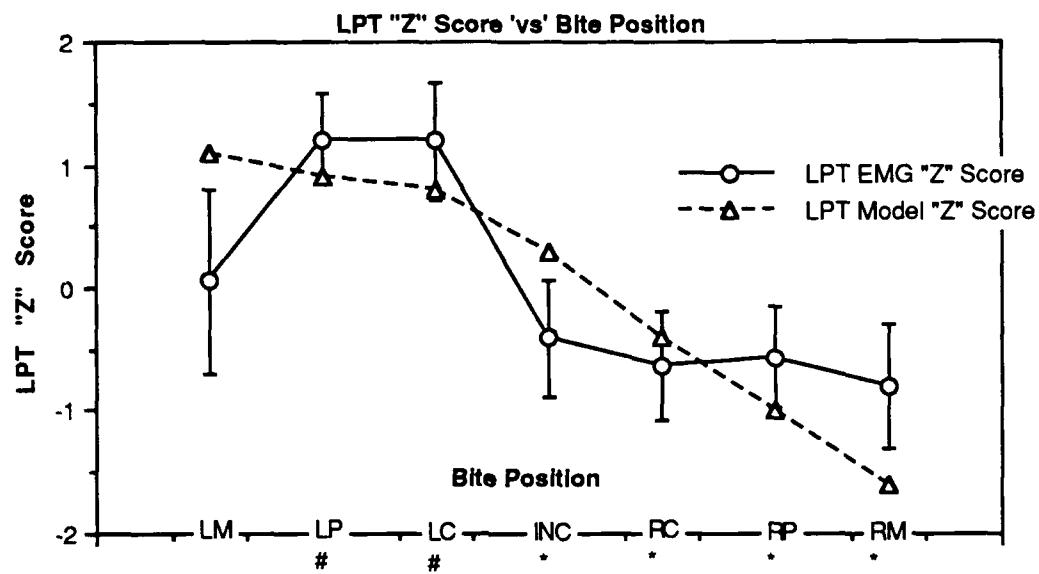


Fig. 7. Data as in fig. 6 for the left posterior temporalis muscle and left temporalis model. Symbol code is the same as in figure 6.

Quantitatively, no significant difference in EMG "Z" scores was found among the contralateral molar, premolar, canine and the incisor biting positions (labeled "*" in figures 6 & 7, $p > 0.1$, FLSDT). A distinct rise in activity was noted from the incisor biting position to the ipsilateral canine position, in keeping with model predictions. From the ipsilateral canine and premolar positions to the molar on the ipsilateral side, a significant drop in activity was noted (Sheffe, $p < .05$). These findings are in contrast with the model which predicted increasing activity on the contralateral side while the EMG data showed no significant upward tendency. Also the

model predicted increasing activity from the ipsilateral canine and premolar area to the ipsilateral molar while the EMG data showed a significant decline in this area.

Anterior Temporalis Muscles: Qualitative evaluation of the anterior temporalis data indicated a pattern of activity that generally increased from the contralateral molar position to the ipsilateral canine or premolar position which compared favorably with the model's prediction (Figures 8 & 9). Departures from the model's predictions occurred on the ipsilateral side where a significant decrease in EMG activity (Sheffe, $p < .05$) was noted from the ipsilateral premolar to the ipsilateral molar positions while the model predicted increasing activity.

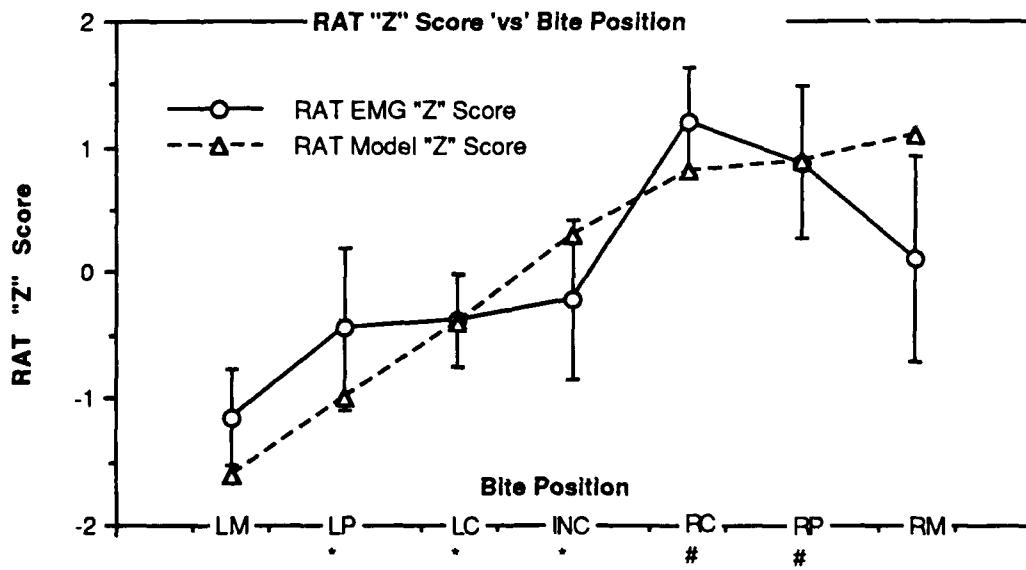


Fig. 8. Data as in fig. 6 for the right anterior temporalis muscle and right temporalis model. Symbol code is the same as in figure 6.

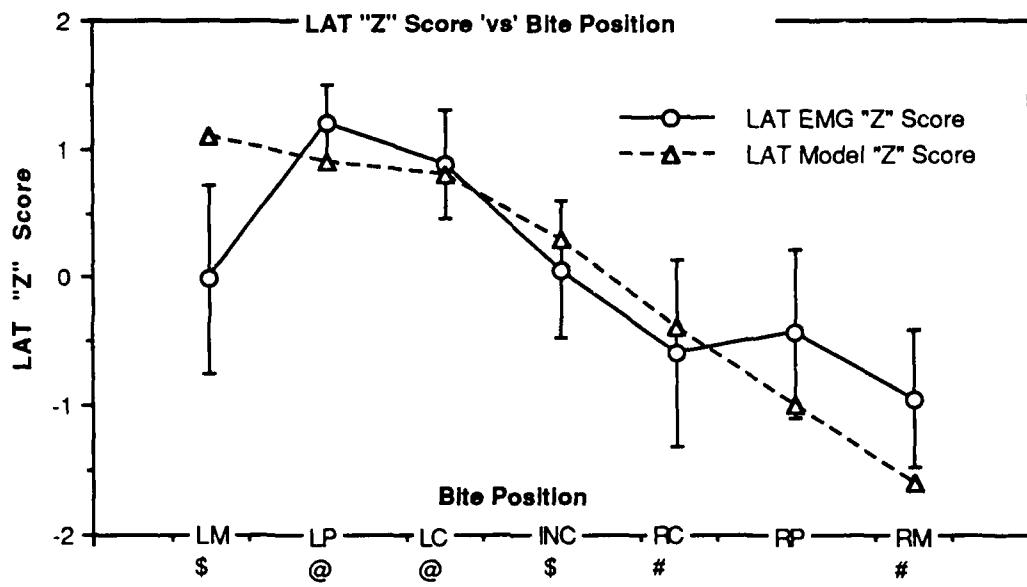


Fig. 9. Data as in fig. 6 for the left anterior temporalis muscle and left temporalis model. Symbol code is the same as in figure 6.

In summary, the most striking departure of the EMG data from model predictions for both anterior and posterior temporalis muscles occurred on the ipsilateral side where in all four muscles, EMG activity dropped significantly from the canine/premolar position to the molar position while the model predicted and increasing activity pattern for this area.

Anterior and Posterior Temporalis Muscles Compared: The similarity between the EMG activity of the RAT and RPT muscles and

between the LPT and LAT muscles can be noted in figures 10 & 11. This suggests that, at least under the biting conditions of this study, patterns of activity in the anterior temporalis and posterior temporalis were quite similar.

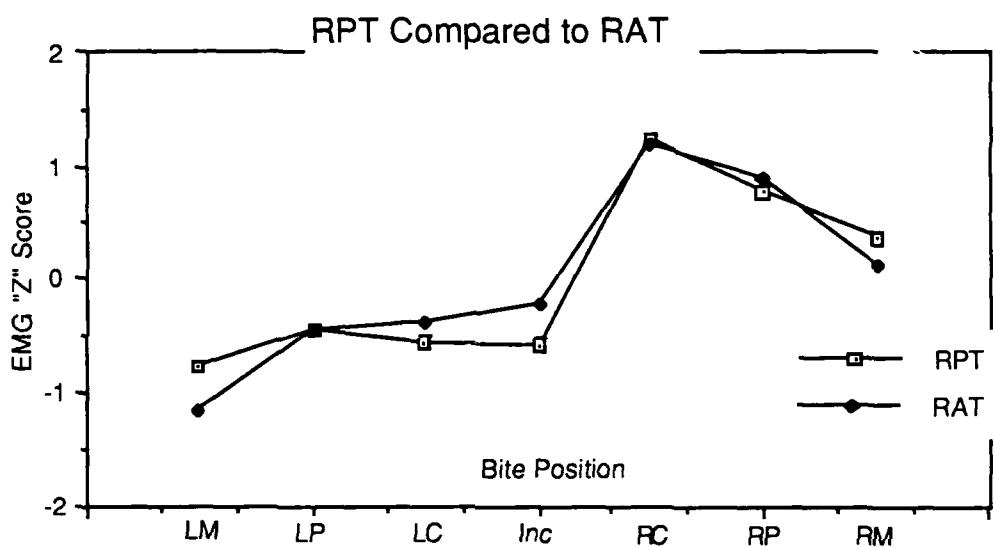


Fig. 10. Mean standardized EMG values for the right anterior and posterior temporalis muscles compared.

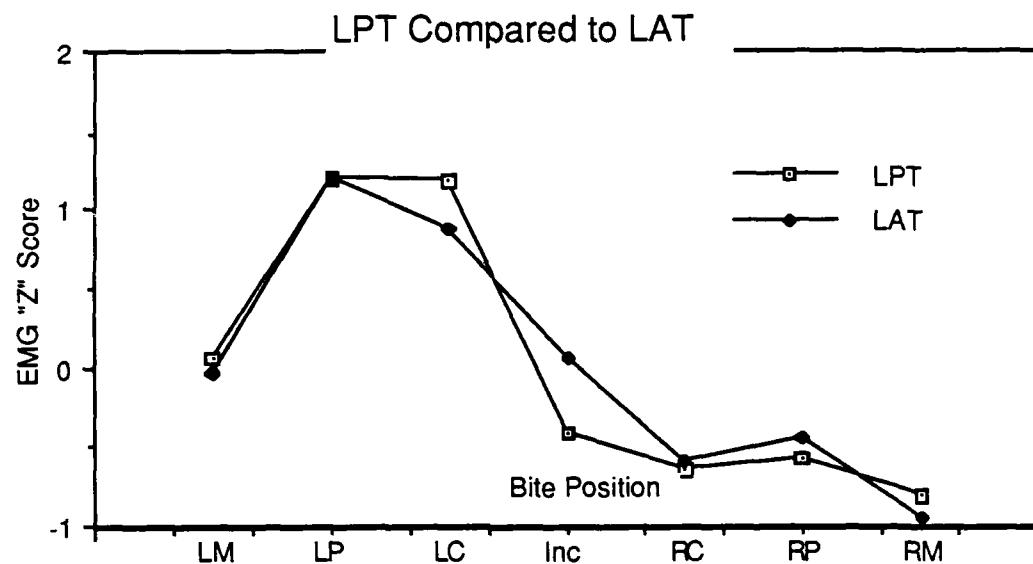


Fig. 11. Data as in fig. 10 for the left anterior temporalis muscle and left posterior temporalis muscles.

Masseter Muscles: Qualitative observation of masseter EMG data suggested maximum activity at the incisors with a symmetrically decreasing pattern toward the posterior biting positions. The right masseter (RM) muscle EMG amplitude pattern failed to differ significantly ($p < 0.1$, FLSDT) between the ipsilateral and contralateral molar biting positions and between the ipsilateral and contralateral premolar positions suggesting symmetry in two of the three paired positions (Figures 12).

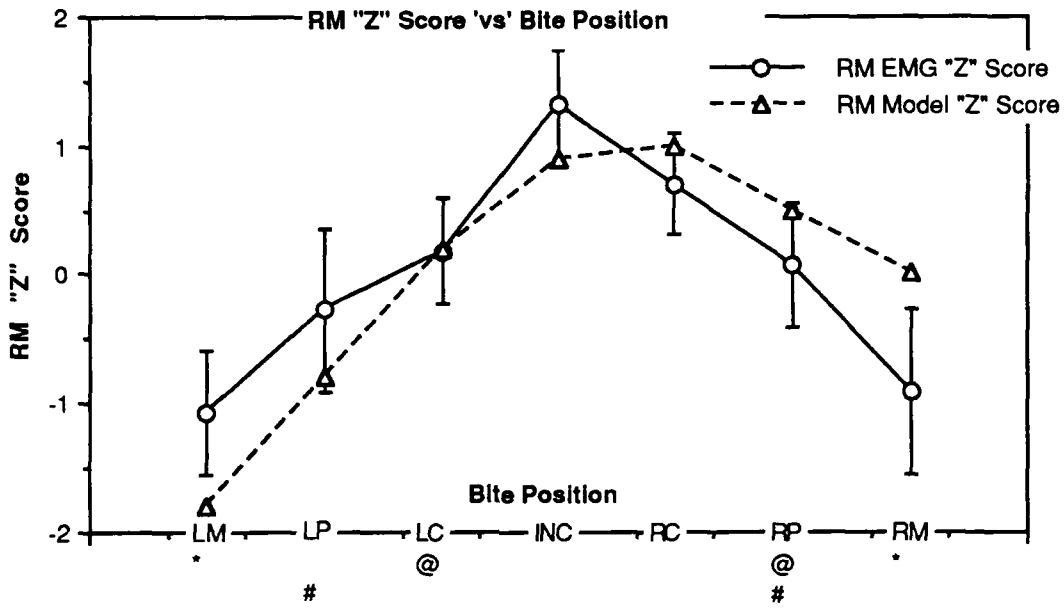


Fig. 12. Data as in fig. 6 for the right masseter muscle and right masseter model. Symbol code is the same as in figure 6.

The left masseter (LM) muscle demonstrated no significant difference ($p > 0.1$, FLSDT) in EMG activity between ipsilateral and contralateral molar, premolar and canine biting positions. Here, all three paired biting positions appear to be symmetrical (Figure 13).

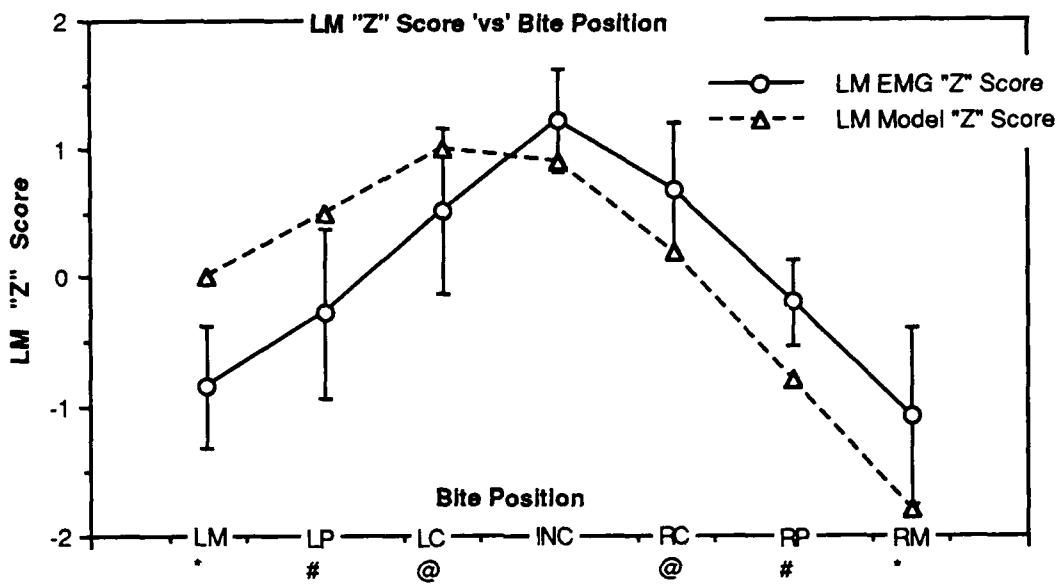


Fig. 13. Data as in fig. 6 for the left masseter muscle and left masseter model. Symbol code is the same as in figure 6.

Thus in the masseter muscles, five of the six pairs of ipsilateral and contralateral biting positions were not significantly different. The model, however, predicted a substantial increase in activity on the ipsilateral biting side compared to the contralateral side.

DISCUSSION

The main findings in this study were, for the temporalis muscle, maximal EMG activity when biting was on the ipsilateral canine or premolar and decreasing activity when moving away from this position. For the masseter muscle, maximum activity occurred at the incisors and fell off symmetrically as the bite position moved posteriorly.

The graphical results were remarkably consistent despite the absence of control for occlusal variations among subjects in the sample, the differences in bite forces the subjects used, and some unavoidable placement errors with the bite fork. Particularly striking was the symmetry in the masseter. For example, in the left masseter, each adjacent biting position was significantly different yet, corresponding bite positions on the opposing sides were not.

Comparison with other muscle function studies: Our findings indicated increasing activity in the ipsilateral temporalis muscle as the bite position is moved posteriorly from the incisors until reaching the canine or premolar area after which decreasing activity was found in the molar area. This finding is in general agreement with MacDonald and Hannam (1984b) who found increased activity in the temporal muscles as the bite point moves posteriorly. The discrepancy between our data and theirs in the molar area of the temporalis may be due to the fact they did not control for bite

force. Our results corroborate theirs regarding decreasing masseter activity as the bite point moves posteriorly, however, we found symmetric activity in the masseter while MacDonald and Hannam (1984b) found the ipsilateral masseter to be more active than the contralateral although both sides showed overall decreasing activity. We are also in agreement with MacDonald and Hannam (1984b) regarding significantly increasing activity in the ipsilateral temporalis at the canine biting position compared to the incisal biting position. Our data consistently showed the increase from the incisor to the canine position to be the greatest increase in activity between any two bite positions in the temporalis muscles.

Moller (1966) found that temporalis activity decreased to almost resting level during a maximal incisal bite. Wood (1986) suggested that muscle activity is dependent on the number of incisal contacts and found increased temporalis activity in subjects having anterior wear facets. MacDonald and Hannam (1984b) also noted increased temporalis activity when an incisal acrylic biting block was used that covered canine to canine compared to a block that covered only the incisors. In our study, the transducer may have provided enough contact area at the incisors to allow the increased temporalis activity above the resting level that we noted.

Comparison of the data to the models: Since our EMG data were recorded during unilateral biting, muscle and joint forces were presumably asymmetrical in all cases except perhaps the incisal biting position. As Pruim's et al. (1980) and Barbenel's (1974)

models were two dimensional, they required occlusal load input to be balanced bilaterally and only produced symmetrical muscle force solutions. Osborn and Baragar's (1985) model may have been capable of three dimensional asymmetric solutions, but only symmetrical loading results were presented in their paper. As a result, our data can only be compared with Smith's et al. (1986) model since it accepts as input asymmetric unilateral occlusal loads and readily calculates asymmetric muscle and joint solutions.

Smith's et al. (1986) model treats the temporalis as a single muscle and the data support this except in the posterior temporalis on the contralateral side where a plateau of low activity was apparent. This pattern was not as distinct in the anterior temporalis where the contralateral side more closely resembled the model. However differences in the activity level between the anterior and posterior portions of the temporal muscle were noted by, MacDonald and Hannam (1984b) They found a retrusively directed intercuspal clench resulted in posterior temporalis activity greater than anterior temporalis while a protrusively directed intercuspal clench resulted in lower posterior temporalis activity. Thus, the similarity of response in the anterior and posterior portions of the temporalis muscles that we found should not be generalized beyond the vertical biting situation used in our study.

It is assumed by the model that the medial pterygoid muscle is an extension of the masseter and that they act synchronously. However, Wood (1987) found that in a vertical clench with the

canine teeth edge to edge, the ipsilateral masseter is more active than the contralateral masseter and ipsilateral medial pterygoid activity is lower than that of the contralateral medial pterygoid. Thus it would appear that in some instances of isometric biting, the masseters and medial pterygoids act independently. This may explain some of the discordance between EMG data and model predictions. Future plans for the model include incorporation of medial pterygoid muscles, and this may produce better agreement of model and EMG activity.

Direct statistical comparison of the EMG data to the model is difficult due to the lack of reliable proportionality constant relating EMG activity to bite force. Conversion of both model predicted muscle force and EMG data to standard scores allowed direct comparisons between the patterns of EMG data and the pattern of model force predictions by forcing the variation in the means of each pattern to be equal. This procedure forced the maximum and minimum values for both the force predictions and the EMG data into the same range while maintaining patterns of changing activity thereby, creating optimal conditions for a favorable comparison of model and EMG data.

Predictions from the model were based on an input set of parameters that included origins and insertions of muscles, mandibular arch width and length, and points of bite force application. Some of these parameters are difficult to estimate on dry skulls, e.g. choosing a point in the temporalis muscle

representative of all its multidirectional fibers. Accurately localizing these points on live subjects would be even more difficult. Throckmorton (1985) found that muscle force direction had a large effect on joint reaction force due to its influence on the length of the moment arm. He suggested that very precise determinations of muscle force directions was necessary to reliably calculate joint reaction forces and, presumably, other parameters involved in model solutions. Weijs (1980) has suggested that the direction of jaw muscle forces may constantly change during function and assigning a single direction for each muscle is probably impossible. Currently, there is no reliable method of determining the direction of jaw muscle forces (Throckmorton, 1985). The lack of accuracy in identifying these points may explain some of the discrepancy between model and EMG data.

Another source of error is the mandibular opening required to accommodate the force transducer. The model predictions used in this comparison are based on a vertical dimension of zero while the EMG data were collected at an incisal vertical dimension of approximately 8 mm and enough protrusion to bring the incisors to an edge to edge relationship. The amount of protrusion required varied with the type of occlusion. Subjects with relatively steep condylar guidance and who protruded to attain an incisal edge to edge relationship maintained a relatively flat mandibular occlusal plane. Subjects with Class III type occlusions who did not protrude much to attain incisal edge to edge relationships had more of an

inclined mandibular plane relative to the maxillary plane. Although thinner rubber pads were used on the biting tabs of the force transducer for posterior bites, some inter and intra-subject variation in vertical dimension between biting positions was unavoidable, introducing another possible inconsistency in the EMG data. Later versions of the model give solutions for vertical dimensions other than zero and this may lead to closer approximation of data and model.

We originally attempted to control vertical dimension and mandibular position by using custom fabricated acrylic biting blocks. Paradoxically, this resulted in more variability in EMG activity recordings than did the rubber biting pads. We attributed this to possible unintentional introduction of lateral forces which would not be sensed by the transducer due to its design, but would be recorded in the EMG activity.

Since all the muscles in this study were externally accessible, surface electrodes were used. Belser and Hannam (1986) found no significant difference between normalized EMG activity recordings from surface bipolar electrodes and paired fine-wire electrodes placed between the surface electrodes. Lack of invasiveness and favorable accuracy when compared to fine-wire electrodes made the surface electrodes a logical choice.

Considerable variability is inherent in EMG activity even when the same bite is repeated at the same bite force without repositioning the transducer or the mandible. For this reason, making precise

comparisons of model predictions and EMG data was not possible. Conversion of EMG activity and model prediction data to standardized scores reduces some of the variability. Yet, EMG activity can only be considered a rough estimate of muscle force and considering the above mentioned sources of error, the departures of the EMG activity patterns from the model predictions in some areas cannot be considered sufficient evidence to disprove the model. These discrepancies do, however, indicate that model predictions may also be only a rough estimate of actual physiologic phenomena and factors such as muscle force direction and independent activity of different sections of the same muscle which cannot be accounted for in the current model may play a significant role.

Hylander's (1979) evidence from Galago and Macaca monkeys indicated that differences in mandibular strain patterns occurred when subjects repeatedly bite on a transducer with the same force and at the same biting position. He suggested that these differing strain patterns occurring while bite position and magnitude did not change indicated differing patterns of muscle activity. This suggests that, at least in monkeys, force distribution among the muscles does not follow a precise reproducible pattern. If this phenomena is present in humans as well, it may explain some of the large variability often encountered in EMG activity studies. Also, it is difficult to account for this kind of variability in model representations of the masticatory system.

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Table 1, Subject #1

TRIAL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	5.3	2.5	6.7	4.0	5.0	5.2
L Premolar	4.1	5.3	7.1	6.4	6.4	5.5
L Canine	3.3	4.5	7.3	6.5	8.6	12.1
Incisors	3.3	2.8	6.4	5.0	11.2	12.8
R Canine	5.6	2.0	9.3	3.5	10.2	15.0
R Premolar	7.1	1.0	10.6	4.1	9.6	9.4
R Molar	5.5	2.5	7.3	3.8	7.1	7.5

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	4.7	2.7	6.3	3.7	5.6	6.8
L Premolar	4.4	3.9	7.3	6.3	6.9	9.7
L Canine	3.4	5.4	6.4	6.4	8.3	11.7
Incisors	3.5	3.1	6.8	5.0	11.3	12.9
R Canine	7.5	1.7	13.4	3.3	10.3	13.2
R Premolar	7.7	3.0	11.7	4.2	10.4	10.8
R Molar	7.5	3.2	7.3	4.0	5.9	7.2

Table 2, Subject #2

TRIAL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.3	7.8	4.1	10.1	7.0	7.2
L Premolar	5.8	14.8	7.6	13.8	8.4	8.2
L Canine	7.6	12.7	8.4	12.8	9.3	9.2
Incisors	9.1	11.7	9.1	12.8	10.4	8.5
R Canine	8.7	11.3	9.4	13.4	12.3	8.4
R Premolar	10.1	10.0	9.7	12.4	11.4	7.6
R Molar	10.0	4.0	10.8	5.3	10.5	5.4

TRIAL # 2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.2	7.5	2.5	9.4	7.7	6.8
L Premolar	7.1	13.9	8.1	13.8	9.4	9.1
L Canine	7.2	12.6	7.5	11.8	9.1	8.4
Incisors	8.9	12.9	9.3	13.6	11.0	7.1
R Canine	9.7	9.1	9.8	13.0	12.8	7.3
R Premolar	11.3	7.5	10.8	10.9	9.9	6.8
R Molar	8.7	3.4	9.9	4.2	9.8	5.0

Table 3, Subject #3

TRIAL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	5.0	2.8	6.9	4.1	6.0	9
L Premolar	9.5	11.0	11.1	11.1	7.6	9.4
L Canine	4.7	12.2	6.9	13.1	9.8	13.2
Incisors	3.4	2.4	7.6	10.2	11.5	14.3
R Canine	9.5	4.2	13.4	6.3	11.0	12.7
R Premolar	6.3	5.2	9.8	8.5	8.3	11.2
R Molar	4.0	6.7	6.2	7.2	7.8	8.1

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	7.5	6.5	8.4	7.0	7.2	8.2
L Premolar	7.7	11.6	9.4	11.5	8.4	9.1
L Canine	4.8	11.3	16.6	11.8	9.4	10.8
Incisors	2.4	3.0	8.6	10.5	11.5	14.1
R Canine	9.1	3.2	13.9	4.9	10.4	12.3
R Premolar	7.6	5.0	11.4	7.2	8.3	10.9
R Molar	4.7	7.5	7.6	7.5	8.0	9.3

Table 4, Subject #4

TRIAL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	1.1	5.4	1.2	6.9	5.6	7.2
L Premolar	1.5	13.8	1.9	10.0	8.0	11.0
L Canine	2.0	12.7	2.7	10.2	7.8	10.9
Incisors	1.5	3.0	2.2	5.4	9.2	14.4
R Canine	9.9	4.1	7.7	6.1	6.7	8.4
L Canine	9.7	4.2	8.3	4.6	6.0	9.0
L Molar	9.3	2.2	6.8	3.2	2.9	5.2

TRIAL #2

	RPT	LPT	RT	LAT	RM	LM
L Molar	1.2	5.6	1.5	7.6	6.8	8.2
L Premolar	1.5	12.0	1.6	9.0	7.6	8.3
L Canine	2.2	10.9	2.0	9.0	7.7	10.7
Incisors	1.7	5.3	4.0	8.2	9.0	14.1
R Canine	7.9	2.5	7.3	4.6	7.5	9.2
R Premolar	10.5	4.2	9.3	5.1	8.2	11.6
R Molar	9.6	1.6	6.5	3.8	2.6	6.2

Table 5, Subject #5

TRIAL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.0	6.6	2.3	4.1	4.0	3.7
L Premolar	3.8	8.2	6.2	6.1	8.6	5.8
L Canine	2.1	6.8	3.3	5.0	8.9	12.7
Incisors	2.8	3.4	4.3	2.8	10.6	14.7
R Canine	7.9	3.1	10.1	2.3	8.9	10.8
R Premolar	8.0	4.7	9.2	4.1	6.5	8.4
R Molar	5.8	3.2	8.5	3.0	5.3	5.7

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.3	8.4	3.1	5.4	4.6	3.3
L Premolar	2.4	8.2	3.2	6.2	5.9	4.6
L Canine	2.0	9.6	2.7	6.5	10.7	8.7
Incisors	2.5	4.0	6.0	2.1	11.7	13.1
R Canine	5.3	3.5	7.2	3.7	7.7	9.0
R Premolar	7.3	4.0	8.5	3.4	6.5	8.8
R Molar	7.3	5.8	7.9	3.3	6.3	3.6

Table 6, Subject #6

TRAIL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	3.7	10.5	5.9	10.1	5.7	3.5
L Premolar	3.6	12.7	6.2	11.4	5.4	3.7
L Canine	4.1	12.8	7.4	10.8	7.8	5.5
Incisors	3.7	6.1	7.2	10.1	9.9	5.8
R Canine	6.9	1.1	9.1	6.7	9.1	5.0
R Premolar	11.8	1.8	8.2	7.5	9.0	4.6
R Molar	13.1	2.0	8.9	6.2	6.4	4.3

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.8	10.2	6.2	10.5	6.8	3.4
L Premolar	3.3	12.9	6.6	10.9	6.5	4.1
L Canine	3.3	13.0	7.0	12.5	10.5	7.1
Incisors	3.1	2.3	7.2	9.5	11.2	5.6
R Canine	11.3	1.1	8.6	7.3	11.1	5.7
R Premolar	10.9	1.8	7.9	8.2	8.5	4.7
R Molar	12.7	2.0	8.6	7.5	6.1	4.4

Table 7, Subject #7

TRIAL # 1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	5.1	2.6	5.9	3.1	5.0	2.5
L Premolar	4.9	6.7	5.5	4.6	6.0	3.1
L Canine	6.4	7.2	8.3	4.4	7.2	3.3
Incisors	6.1	2.6	9.9	2.9	8.5	3.0
R Canine	8.0	3.2	10.1	3.6	6.8	3.6
R Premolar	5.9	3.7	9.9	3.4	6.3	3.2
R Molar	6.4	2.3	8.5	2.0	4.1	2.2

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.4	3.7	5.3	3.4	4.6	2.6
L Premolar	5.6	4.9	6.3	4.3	6.2	3.2
L Canine	5.7	6.1	7.4	4.5	6.4	2.9
Incisors	4.5	3.0	9.1	3.3	8.5	3.9
R Canine	6.7	2.9	9.2	3.0	6.6	2.6
R Premolar	5.9	2.8	10.1	3.1	5.9	2.8
R Molar	6.4	2.3	8.3	2.1	4.1	2.2

Table 8, Subject #8

TRIAL #1

	RPT	LPT	RAT	LAT	RM	LM
L Molar	2.0	5.0	2.9	5.4	6.4	4.3
L Premolar	2.5	4.7	3.3	5.5	8.9	6.8
L Canine	2.0	4.0	3.1	5.1	7.0	7.0
Incisors	2.1	3.2	4.0	5.3	11.2	7.4
R Canine	8.8	1.6	6.3	3.5	10.0	8.6
R Premolar	6.0	2.8	5.1	5.0	7.4	5.9
R Molar	3.4	1.9	3.2	4.1	5.9	4.3

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	1.7	2.3	3.3	4.3	6.9	5.0
L Premolar	1.4	3.4	3.2	5.5	9.5	7.0
L Canine	3.0	5.1	3.1	6.0	6.6	7.2
Incisors	2.4	2.0	4.9	5.1	12.1	9.4
R Canine	8.2	1.5	6.0	5.2	12.6	9.9
R Premolar	4.5	1.6	4.5	4.4	9.1	6.6
R Molar	4.0	3.8	3.8	4.9	7.2	5.3

Table 9, Subject #9

TRIAL #1

	RPT	LPT	RAT	LAT	FM	LM
L Molar	2.0	7.5	3.9	6.3	9.0	6.2
L Premolar	3.0	9.9	4.7	6.7	8.6	6.1
L Canine	2.1	9.6	5.1	5.9	9.2	5.3
Incisors	2.0	2.2	4.0	5.0	10.8	10.4
R Canine	8.5	4.2	7.9	4.8	9.8	8.7
R Premolar	6.8	1.6	10.0	3.6	9.3	6.7
R Molar	3.2	1.7	7.1	4.4	7.4	7.8

TRIAL #2

	RPT	LPT	RAT	LAT	FM	LM
L Molar	1.1	4.2	3.7	4.8	8.0	5.5
L Premolar	2.0	8.9	4.3	5.7	9.6	5.7
L Canine	1.5	8.7	4.7	6.1	8.9	5.3
Incisors	3.4	2.9	5.9	4.7	10.5	9.1
R Canine	4.9	3.5	7.6	4.6	11.2	7.3
R Premolar	6.5	2.0	8.1	4.4	9.3	7.0
R Molar	3.9	2.7	7.3	4.3	5.9	5.5

Table 10, Subject #10

TRIAL #1

	RPT	LPT	RAT	PAT	RM	LM
L Molar	.8	1.9	5.8	5.6	5.4	8.8
L Premolar	.8	1.4	7.0	6.8	6.8	9.3
L Canine	1.0	4.0	7.0	5.8	7.1	9.2
Incisors	.9	1.7	7.5	5.8	9.1	11.3
R Canine	2.5	.8	8.4	5.1	7.3	9.3
R Premolar	1.2	.9	6.8	4.0	6.6	6.3
R Molar	1.4	1.3	6.0	4.4	6.0	5.1

TRIAL #2

	RPT	LPT	RAT	LAT	RM	LM
L Molar	1.0	1.6	5.1	5.7	5.3	8.2
L Premolar	.9	2.6	6.1	5.2	6.3	9.5
L Canine	1.8	2.8	6.6	6.5	7.0	9.8
Incisors	1.5	2.2	7.0	5.6	7.7	9.1
R Canine	2.7	.9	8.4	4.8	8.1	8.9
R Premolar	2.7	1.1	7.4	4.2	7.2	7.2
R Molar	2.0	.8	6.1	3.4	6.0	5.6